Comparison of TOF-ERDA and nuclear resonance reaction techniques for range profile measurements of keV energy implants


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Abstract

A comparative study on the range measurements of keV energy implants by the Time-of-Flight Elastic Recoil Detection Analysis (TOF-ERDA) and conventionally used nuclear resonance reaction methods has been performed for 20–100 keV \(^{15}\text{N}\) ions implanted into crystalline silicon. Range profiles of \(^{15}\text{N}\) atoms were chosen because they can be measured accurately using a very strong and narrow resonance at \(E_p = 429.6\) keV in the reaction \(^{15}\text{N}(p,\alpha\gamma)^{12}\text{C}\) which provides a challenging test for other methods. The measured range profiles were simulated by molecular dynamics calculations where the interatomic N–Si pair potential is deduced from first principles calculations. The electronic stopping power for 20–100 keV nitrogen ions in silicon is deduced from the comparison of the measured and simulated range profiles. The results are discussed in the framework of the applicability of the TOF-ERDA technique for keV energy ion range measurements.

1. Introduction

Elastic Recoil Detection Analysis \(^{1}\) (ERDA) \([1,2]\) is a method by which the observation of recoiled target atoms yields the most direct information about target composition. In conventional ERDA measurements, recoiling atoms of different elements are separated with stopping foils. The foils cause, however, energy straggling and are not very easy to use when several elements need to be separated. Therefore, many different types of ERDA set-ups have been constructed \([3–10]\). One of the most promising techniques is Time-of-Flight ERDA (TOF-ERDA) \([9–14]\), where, in addition to traditional energy measurement, time-of-flight over a known distance is measured for each atom. The mass of each detected atom can be calculated from the classical formula for kinetic energy. Furthermore, when the mass of a particle has been identified, the same equation with a tabulated accurate mass can be used to obtain the energy from the measured time-of-flight \([15,16]\). Accurate time calibration is more straightforward than energy calibration and using the time-of-flight signal instead of the signal from the energy detector can give a better energy resolution, especially for heavier particles. TOF-ERDA systems have been widely used mainly for analyzing thin films and layered structures.

In the Accelerator Laboratory we have systematically studied stopping power and employed range profiles of keV energy implants to deduce stopping power values at these energies \([17–21]\). In this work we present a TOF-ERDA measurement system and its application to depth profiling of ion-implanted concentration distributions. Range profiles of implanted \(^{15}\text{N}\) in crystalline silicon (c-Si) were measured with the TOF-ERDA spectrometer and results are compared with those obtained with the 429 keV resonance in the reaction \(^{15}\text{N}(p,\alpha\gamma)^{12}\text{C}\). This resonance reaction provides one of the best tools for the range measurements of keV energy light ions with the Nuclear Resonance Broadening (NRB) method \([22]\). The measured range profiles are compared with those obtained in Molecular Dynamics (MD) simulations \([19]\). From this comparison, the electronic stopping power of silicon for low energy nitrogen ions is deduced. In order to take into account the damage structure of implanted c-Si in the MD simulations, RBS channeling measurements were also performed.

2. Set up for TOF-ERDA measurements

2.1. Apparatus design

A schematic diagram of the TOF-ERDA measurement system constructed at the Accelerator Laboratory is shown...
in Fig. 1. A high-energy heavy ion beam from the 5 MV tandem accelerator EGP-10-II of the laboratory is directed to a 20-position target holder in the target chamber. The pressure in the chamber is kept lower than 1 μPa. The angle between the sample surface and the incident beam can be chosen freely. In standard measurements it has been 70°, measured from the normal of the sample surface. The angle between the direction of the ion beam and the direction where recoil atoms are detected can be selected in steps of 10° between 20° and 70°. In standard measurements it has been 40°. Measurements can also be done at backscattering angles.

The TOF-ERDA spectrometer system for recoiled particles consists of two timing detectors and an energy detector. The distance between the time detectors can be altered by changing the vacuum tube between them. The current timed flight length is 684 mm. An energy detector is located after the time detectors, in this study at a distance of 1243 mm from the target. The solid angle for the particle detection is 0.19 msr with the flight length and collimators used.

The design of both timing detectors follows that of Busch et al. [23]. Their structure can be seen in Fig. 2. Each timing detector consists of a thin carbon foil (currently 4.3 μg/cm² in the first and 22.8 μg/cm² in the second detector [24]) that emits secondary electrons when a recoil penetrates through it. Electric fields created by potential differences between the foil and grids accelerate and guide the electrons to a microchannel plate (MCP) [25]. The total transmission of the grids for the whole detector system is 72.3%. Secondary electrons from the foils are multiplied by two MCPs in series and subsequently collected by a metal anode. Voltages to foils, grids and MCPs are supplied by a 6.2 kV power source via a 31 MΩ resistor chain that is partially in vacuum. The MCPs are biased with a potential difference of 900 V and are
separated from each other and from the anode by a small
distance and a voltage of 200 V. The total-energy detector
is an ion-implanted silicon detector from the EG & G Ortec
Ultra series. This detector has an active area of 300 mm²
and a depletion depth of 300 µm.

The timing and pulse-shaping electronics consist pri-
marily of conventional NIM modules. The negative anode
signals from the timing detectors are transformed to logical
pulses in two constant fraction discriminator (CFD) units.
Amplification of the anode signals is not necessary. The
output signal from the CFD of the first timing detector is
delayed in a coaxial cable and stops the conversion cycle
of a time-to-amplitude converter (TAC). The output signal
from the CFD of the second timing detector is used as a
start pulse. This reversed start-stop order is used to mini-
mize the dead-time of the TAC caused by a larger solid
angle and therefore a higher count rate of the first timing
detector. By choosing the length of the delay cable and the
TAC time scale, a suitable time region can be obtained.
Currently, flight times up to 210 ns are recorded. The
signal from the energy detector is preamplified and ampli-
fied conventionally. The time and energy pulse-height
signals are converted to digital form in two analog-to-dig-
ital converters (ADC) with a resolution of 4096 x 4096
channels and recorded with a Canberra MPA/PC multipa-
rameter system. The coincidence between timing and en-
ergy signals is detected in the multiparameter system. In
our standard analysis the MPA/PC system is used in a
mode where time-of-flight and energy signals are regarded
to be coincident if they arrive within 350 ns at the input.

2.2. Calibration and characteristics

For characterization of the TOF-ERDA system, several
 calibration spectra were measured. Beams of 4–15 MeV
 H, 7Li, 10B, 12C, 14N, 15N, 16O, 18F, 20Ne, 28Si, 35Cl,
 63Cu, and 69Ga ions from the 5 MV tandem accelerator
 EGP-10-II of the laboratory were scattered from a thick
tantalum target. The scattered ions were measured in a
special mode where each detection of a particle, either in
the time-of-flight or energy detector, was recorded in
addition to the coincident events. The detection efficiency
of the energy detector was assumed to be 100% for each
element, and the relative efficiency of the whole spectrom-
eter system was calculated as the ratio of (1) the number
of coincidence events and (2) the number of particles de-
tected by the energy detector.Measured average detection
efficiency as a function of atomic number is shown in Fig.
3. For hydrogen detection, the efficiency is only a few
percent, and was observed to be energy-dependent. The
efficiency increases with increasing mass and depends
only weakly on energy for heavier elements. At the ener-
gies relevant to the TOF-ERDA analysis, the detection
efficiency can be assumed to be constant, and all elements
heavier than hydrogen can be analyzed with a reasonable
efficiency.

In the time calibration the edge of each energy-TOF
coincident spectrum corresponding to the shortest time-of-
flight (signals from the sample surface) was used. Spectra
were projected on the time axis and the slowing down in
the first carbon foil was taken into account in the calibra-
tion. The time calibration curve did not depend on the
particle mass or energy. A closely similar analysis for
energy signals showed that the energy calibration curve
was a somewhat nonlinear function of both the energy and
mass of an atom. Therefore, the mutivariate method of El
Bouanani et al. [26] was used for energy calibration.

The time resolution of the TOF-ERDA system was
determined by the use of the 5.4565 and 5.49921 MeV
α-particles (28% and 72% relative intensities, respectively)
emitted by a thin 238Pu source [27]. The calculated time-
of-flight difference of the α peaks is 164 ps for the
geometry used. The peaks were not separated in the time-
of-flight spectrum, and only one Gaussian line shape could
be fitted to the composite peak in the spectrum. The time
resolution for α particles is therefore better than 300 ps
obtained at full width at half maximum (FWHM) of the
peak, but worse than 164 ps. It is worth noting that for
heavier particles the secondary electron yield from the
carbon foils is higher, resulting in larger-amplitude timing
signals, which would improve the time resolution for them,
and compensate for the worsening of the resolution caused
by the larger energy straggling in the first foil. The energy
resolution of the semiconductor detector is 18 keV
(FWHM) for α particles and becomes quickly poorer with
heavier particles. The time resolution, however, is not
particle-dependent to the same extent.

Mass and depth resolutions of TOF-ERDA systems
have been studied in the literature for spectrometers closely
similar to that used in this work [11,14,16,26,28-31]. We analyzed mass and depth resolutions of our spectrometer for $^{16}$O at the surface of pure quartz (SiO$_2$). Because the procedure requires similar kind of analysis methods as used in quantitative analysis of actual samples, the results are given in Section 4.1.

3. Measurements of $^{15}$N-ion-implanted silicon samples

3.1. Samples

Two sets of samples were prepared by implanting 20, 40, 60, 80, and 100 keV $^{15}$N$^+$ ions into pure (100) silicon crystals at the 100 keV isotope separator of the laboratory. In order to avoid channeling of the implanted ions the Si(100) samples were tilted 8° relative to the beam and the (100) direction. The implantation dose was $1 \times 10^{16}$ ions/cm$^2$ for the first set of the samples and $1 \times 10^{15}$ ions/cm$^2$ for the second set of the samples.

3.2. TOF-ERDA measurements

The two primary beams used to recoil target atoms consisted of 37 MeV $^{197}$Au$^+$ ions supplied by the 5 MV tandem accelerator EGP-10-II of the laboratory. The beam current was about 7 nA (electric). The beam spot on the target was 3 × 3 mm$^2$. Each sample with the ion-implantation dose of $1 \times 10^{16}$ ions/cm$^2$ was measured for about half an hour to obtain a reasonable counting statistics, and each sample with the implantation dose of $1 \times 10^{15}$ ions/cm$^2$ for about an hour. In addition to the actual samples, a sample of pure quartz (SiO$_2$) was measured to study mass and depth resolutions.

The beam of $^{197}$Au ions instead of lighter ones, e.g. $^{35}$Cl, was chosen for the TOF-ERDA measurements in order to improve the depth resolution in the surface layer of the sample. The fact behind this is the high stopping power of materials for Au atoms. The high atomic number of the Au atoms results also in a large scattering cross section. Furthermore, Au atoms scattered from target atoms lighter than 126 u do not enter directly the TOF-ERDA spectrometer in the geometry used. This reduces the spectrometer dead-time radically, and radiation damage of the energy detector is prevented. In the current study these facts were considered to be more important relative to the disadvantages of using heavy primaries (greater radiation damage in the sample material and lower energy of light recoils due to smaller kinematic factors [2], resulting in worse energy and mass resolutions [31]).

3.3. NRB measurements

The concentration profiles of $^{15}$N atoms were measured by NRB using the narrow ($I \approx 124$ eV [32]) 429.6 keV resonance in the reaction $^{15}$N(p,$\alpha\gamma$)${}^{12}$C. The proton beams of about 1 µA were supplied by the 2.5 MV Van de Graaff accelerator of the laboratory. The beam energy resolution was about 1.5 keV (FWHM), corresponding to a depth resolving power of about 24 nm at the sample surface. The $\gamma$ radiation ($E_\gamma = 4.43$ MeV) was detected in a 12.7 cm (diameter) × 10.2 cm NaI(Tl) crystal located 2 cm from the target and at an angle of 0° relative to the proton beam direction. The detector was shielded against the background radiation by 5 cm of lead. The beam was focused to a spot of 3 × 3 mm$^2$. The silicon sample was tilted 7° relative to the proton beam to avoid channeling of the probing beam [33]. The charge deposited by the probing beam was 20–100 µC per each measured point. The corresponding measuring time was between 30 min and 2 h for the whole range profile.

3.4. RBS channeling measurements

The crystallinity of the implanted samples was studied in RBS channeling measurements. The channeling 1.5 MeV $^4$He$^+$ ions were supplied by the 2.5 MV Van de Graaff accelerator of the laboratory. The angular divergence of the incident beam was less than 0.02°. Backscattered particles were analyzed with a 50 mm$^2$ Si(Li) detector located at 170° with respect to the incident beam and at a distance of 65 mm from the target. The particle detector subtended a solid angle of 7.9 msr. The energy resolution of the detector was 17 keV (FWHM). The samples were mounted on a precision goniometer, and the beam was aligned with respect to the (100) axis to give minimum backscattering yield. The concentrations of the displaced atoms were obtained by comparing spectra taken with an implanted sample aligned so that the (100) axis was in the beam direction (aligned implanted spectrum) with the same sample rotated so that a maximum yield was obtained (random spectrum), and with an unimplanted sample oriented so that the (100) axis was in the beam direction (aligned virgin spectrum). The relative ion doses for different spectra were obtained with an accuracy of better than 2% by using a beam chopper with a separate pulse analysis system.

4. Results

4.1. TOF-ERDA measurements

The first part of the analysis of the TOF-ERDA data obtained from the $^{15}$N$^+$ implanted samples ($1 \times 10^{16}$ ions/cm$^2$) was done with the CERN software package PAW (Physics Analysis Workstation) [34]. PAW is an analyzing and presentation environment that can handle multi-dimensional list data either interactively or in batch mode. One of the measured energy-TOF spectra is shown in Fig. 4.
By using linear time calibration and multivariate energy calibration [26], the mass of each detected particle was calculated using the nonrelativistic formula for the kinetic energy. The resulting three-parameter data was projected to TOF-mass spectra as illustrated in Fig. 5. From these spectra, detected $^{15}$N, Si and C and O contaminants were easily separated by setting a window on the mass axis for each element. Because there were no overlap between different masses more precise methods [16,31] were not needed. Distributions of $^{15}$N concentrations in the samples with the implantation dose of $1 \times 10^{15}$ ions/cm$^2$ could not be deduced reliably because signals from bulk Si and O contaminations at the surface produced relatively high background in the N spectra and resulted in high statistical uncertainties of measured range profiles.

Data for each element were projected to time-of-flight spectra. Time information was used for further analysis because the depth resolution obtained from the time-of-flight measurements was better than the one from the energy measurements. The time spectra for each element were mapped to non-equidistant energy spectra by calculating the energy of each time channel using the tabulated atomic mass [15] and multiplying the yield in each channel with the Jacobian of the time-to-energy transformation [35]. The non-equidistant energy spectra were then mapped to equidistant energy spectra illustrated in Fig. 6. These energy spectra were used in calculating the concentration profiles as a function of depth.

In the analysis of the energy spectra, a computer program of the TOF-ERDA group at Tokyo Institute of Technology [36,37] was used to obtain the concentration distributions of the $^{15}$N implants. The program was modified to use TRIM-95 stopping power [38] or an experimental stopping power instead of the original ZBL stopping power [39]. Even though at the projectile energies used ($E_{\text{lab}} = 0.19$ A MeV) screening effects cause deviation of the elastic scattering cross-section from the Rutherford cross-section they were neglected in the analysis. The screening was estimated to yield only a very small correc-
Fig. 7. Measured concentration profiles of ion-implanted \( ^{15}\text{N} \) as a function of depth for the samples with implantation dose of \( 1 \times 10^{16} \) ions/cm\(^2\). Implantation energy is given in each subfigure. TOF-ERDA profiles are shown with closed circles. NRB profiles are shown with open circles. The number of nitrogen atoms is normalized to \( 1 \times 10^{16} \) atoms/cm\(^2\) for all distributions.

Fig. 8. Measured range profiles of \( ^{15}\text{N} \) ions as a function of depth for the samples with implantation dose of \( 1 \times 10^{16} \) ions/cm\(^2\). Implantation energy is given in each subfigure. TOF-ERDA profiles are shown with closed circles. NRB profiles are shown with open circles. The number of nitrogen atoms is normalized to \( 1 \times 10^{16} \) atoms/cm\(^2\) for all distributions.

For characterization of the TOF-ERDA spectrometer, the mass resolution for \( ^{16}\text{O} \) was deduced. Oxygen was chosen because it is easy to measure with a \( \text{SiO}_2 \) calibration sample and its mass is similar to that of the mass of \( ^{15}\text{N} \). The measured \( \text{SiO}_2 \) spectrum was transformed to a TOF-mass spectrum. A near-surface time-of-flight slice of oxygen counts was projected onto the mass axis and a Gaussian line shape was fitted to the mass spectrum. This resulted in a mass resolution of 0.4 u (FWHM). With increasing depth and mass the resolution becomes worse. The \( \text{SiO}_2 \) spectrum was converted to depth profiles with the method described above. By fitting a convolution of a step function with a Gaussian to the oxygen concentration profile, the depth resolution of 12 nm (FWHM of the Gaussian) at the sample surface was obtained.

4.2. NRB measurements

The concentrations of the \( ^{15}\text{N} \) atoms were obtained by comparison of gamma-ray yields with those measured with a TiN standard. In the calculation of the depth scale, experimental electronic stopping power values of silicon for protons [42, 43] were used. Results from measurements of \( ^{15}\text{N} \) range profiles are shown in Fig. 7 and 8. The measurements with the \( 1 \times 10^{15} \) N/cm\(^2\) and \( 1 \times 10^{16} \) N/cm\(^2\) samples showed only minor differences between these two sets of data as demonstrated in Fig. 8.

4.3. RBS channeling measurements

In order to study the damage in the nitrogen implanted c-Si samples, the concentrations of the Si atoms displaced from the lattice sites were obtained by comparing the spectra from the aligned virgin and random silicon sample with the spectra from the aligned implanted samples [44]. The depth scale was established by using the program Gis3 [45]. It was observed that the samples with the ion-implantation dose of \( 1 \times 10^{16} \) ions/cm\(^2\) were completely amorphous. In the samples with ion-implantation dose of \( 1 \times 10^{15} \) ions/cm\(^2\), maximum concentrations of displaced atoms were observed to be about 20 at.\%.

5. MD simulations

The measured range profiles shown in Figs. 7 and 8 were simulated using the molecular dynamics (MD) method and a simulation code developed in our laboratory [19]. The interatomic potential employed in the MD simulations was obtained by calculating the total energy of the N–Si dimer using density-functional theory (DFT) at the local-density approximation (LDA) level [46] using the DMol program package [47, 48]. To obtain the interatomic force function, the total energy and its derivative were calculated
as a function of the interatomic distance $r$ at dense intervals. To check the reliability of the DMol results, the total energy of the dimer was also calculated for a few internuclear distances using a fully numerical Hartree–Fock–Slater ($X_a$) method [49,50].

Comparison of the DMol and the numerical Hartree–Fock–Slater results showed that using the standard set of orbitals in generating the DMol basis functions [51] produces an interatomic potential which is about 3–4% stronger than the Hartree–Fock–Slater result in the energy region 0.1–10 keV. By augmenting hydrogenic orbitals [51] to the standard DMol orbitals for Si, good agreement (difference less than 1%) with the Hartree–Fock–Slater results was obtained. In the MD simulations, the repulsive potential and force were calculated by using a spline interpolation of the potential energy and force points obtained in the DMol calculations.

The electronic stopping power of silicon for keV energy nitrogen atoms was first obtained from the TRIM-95 code [38]. Range profiles were calculated for both crystalline and amorphous silicon. The atomic coordinates for the latter were based on ab initio MD simulations [52–54].

Before comparing the calculated range distributions with experimental results, they were convoluted with the experimental depth resolution. In the case of TOF-ERDA, resolution effects of the time-of-flight measurements, detector solid angle, multiple scattering of the Au beam and recoiling N ions, and electronic straggling of the Au beam and recoiling N ions were included [30,37,55]. In NRB measurements the energy resolution of the incoming proton beam and the electronic straggling of the probing beam determine the depth resolution. In calculating the elec-

![Fig. 8. Results from the NRB measurements. Implantation energy is given in each subfigure. Measured range profiles for the samples with the ion-implantation dose of $1 \times 10^{16}$ ions/cm$^2$ are shown with closed circles, and for samples with the ion-implantation dose of $1 \times 10^{15}$ ions/cm$^2$ with open circles. Simulated profiles for amorphous silicon are shown with solid lines. Simulated range profiles have been obtained with corrected stopping powers of Si for low-energy nitrogen ions and are convoluted with NRB depth resolution. The total number of implanted atoms is scaled to $1 \times 10^{16}$ atoms/cm$^2$ for each distribution.](image)

![Fig. 9. Comparison of MD simulations with different parameters for a sample with $1 \times 10^{16}$ 100 keV N$^+$ ions/cm$^2$. In (a) simulated profiles with corrected N stopping power for amorphous silicon are convoluted with depth resolutions of TOF-ERDA (solid line) and NRB (dashed line). The insert shows the calculated depth resolution of the methods as a function of depth. Resolution is defined as FWHM of a distribution obtained with the methods for an assumed delta-function concentration of $^{15}$N. In (b) measured NRB profiles are shown with closed circles, distributions simulated for amorphous silicon with a dashed line (stopping power from TRIM-95) and for amorphous silicon with corrected N stopping power with a solid line. If the samples are assumed to have the structure of c-Si the range profile shown by the dotted line is obtained in the simulations using the corrected stopping power for low-energy N.](image)
In the case of TOF-ERDA measurements the effect of multiple scattering of the beam and recoiling particles near the surface. Deeper in the sample the effect of electronic straggling the value given by the Bohr model had to be multiplied by 0.8 to achieve a good agreement between measured and simulated range distributions. This is in a reasonable agreement with our previous result for 620 keV protons and the theoretical estimations of Chu and Yang et al. The quality of the data obtained with the technique is comparable to the quality obtained for nitrogen with NRB profiling of oxygen. However, it is difficult to obtain with surface erosion due to sputtering during the $^{15}$N implantation. Since the implantations were carried out with equal doses, the largest erosion effect can be expected from the lowest energy implantations.

The electronic stopping power given by the TRIM-95 code has velocity dependence of the form $S_e \propto v^{0.75}$, where $S_e$ is the stopping power and $v$ the ion velocity. To our knowledge, the only experimental work published on electronic stopping power of silicon for nitrogen at the energy range of the present work is that of Grahmann and Kalbitzer. They obtained a velocity proportional electronic stopping power ($S_e \propto v$). Simulations were also performed using this stopping power. The best fit was achieved by scaling the stopping power of Ref. [59] by 1.14. However, the agreement between the measured and simulated profiles was worse than in the case of TRIM-95 type stopping power.

It should be noted that in fitting the simulated profiles to NRB data both the correction factor of the electronic stopping power for N ions and the electronic straggling of the NRB proton beam can be determined because they affect the distributions in different ways. By scaling the stopping power essentially the depth scale of the profile is changed. The straggling only affects the width of the distribution. Consequently, the correction factor of the electronic stopping power giving the best fit between measured and simulated profiles was insensitive to the scaling factor of the proton beam straggling.

Simulated profiles for one of the implantation energies using both TRIM-95 and corrected $^{15}$N stopping power values are shown with experimental results in Fig. 9. The differences between the calculated range profiles for amorphous and crystalline silicon are illustrated in Fig. 8. When the Dmol repulsive potentials which had been calculated without addition of the hydrogenic orbitals were used in the analysis, the electronic stopping power obtained was roughly 6% smaller than the present results.

### Table 1

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<th>$v / v_0$</th>
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a) 18 keV $^{15}$N atoms.
b) 100 keV $^{15}$N atoms.
TOF-ERDA as good counting statistics as in NRB with the largest cross sections. Furthermore, one of the main difficulties with TOF-ERDA is that its accurate use requires knowledge of stopping powers of both the probing ions and the detected recoiled ions. On the other hand, if the concentration depth profile is known, TOF-ERDA measurements can be used in obtaining the stopping power values for either probing or recoiling ions.

In conclusion, it was demonstrated that range profiles of keV nitrogen atoms can be measured as reliably with TOF-ERDA as with NRB, when the implantation doses are of the order of $1 \times 10^{10}$ ions/cm$^2$ or larger. The range profiles for implantation doses of the order of $1 \times 10^{15}$ ions/cm$^2$ could be analyzed if long measurement times (several hours per sample) could be tolerated. By using Au atoms in the probing beams, the depth resolution of TOF-ERDA deep inside the sample is better than that of NRB in spite of the fact that the narrow 429 keV resonance of the reaction $^{15}\text{N}(p,\alpha)^{12}\text{C}$ is used in NRB. The accuracy of the NRB results depends on the stopping power of the probing protons, the accuracy of the TOF-ERDA results depends on the stopping power of both incoming Au and recoiling N atoms. Stopping powers of silicon known experimentally for protons and nitrogen atoms indicate that the stopping power for gold in the velocity region of $v/v_0 = 2.44-2.75$ ($E = 29-37$ MeV) is in agreement with the TRIM-95 values. Range profiles obtained with MD and Dmol calculations for 20–100 keV N ions showed that the electronic stopping power values given by the TRIM-95 program for N are 6% too large.

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